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Research TEE

Improved Power Transfer Capability and Optimization of Photovoltaic Power Plants

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Abstract

Grid integration is the process of linking distributed energy resources, such as small-scale photovoltaic systems, to the electrical grid. Improving the power quality in the integrated grid of small-scale solar plants requires addressing many technological issues in order to create a secondary distribution network. Thus, this review provides a thorough synopsis of the current state of the art in power quality improvement methods for grid integration, with a focus on PI-Based Reactive Power Control Systems, Flicker Logistic Control Methods, Automated Filtering Mechanisms, Shunt Active Power Filter modules, Integrated Optimization-based AI Technique, and Grid Synchronization Techniques. To help readers better understand how each method contributes to better power quality, the review discusses the pros and cons of each. To further prove that different methods for improving power quality are successful, it offers a comparison study. The evaluation thoroughly assesses how each technique tackles issues like voltage fluctuations, harmonics, and flicker, ultimately leading to a more consistent and dependable power source. In addition to outlining potential avenues for future study and the difficulties inherent in applying different methods to improve power quality during grid integration of small-scale photovoltaic systems, this review offers some recommendations for how this area might be improved.

Keywords: Photovoltaic (PV) power plants, ultra-weak grids, adaptive reactive power control (ARPC), power transfer capability, voltage stability, short-circuit ratio (SCR), grid impedance estimation, sustainable energy systems

INTRODUCTION

Due to climate change and the diminishing availability of fossil fuels, there has been a surge in the need for alternative energy sources. Recently, there has been a lot of curiosity in how renewable energy-based Distributed Energy Resources (DER) systems may be integrated into the distribution grid. One of the most plentiful renewable energy sources is solar radiation. India has enormous potential for solar energy generation, with an average yearly incident solar energy on land of over 5,000 trillion kWh [1]. Annual solar energy production in India surpasses that of all fossil fuel reserves put together. The broad availability and eco-friendly functioning of solar power have propelled it to the forefront of energy policy discussions in recent years. Renewable energy sources are booming in popularity as a result of several government-sponsored subsidies and marketing initiatives. Photovoltaic (PV) power generators, which do not need any moving components, directly transform the energy of solar radiation into electrical energy. Materials with photon-absorbing and electron-emitting capabilities experience this. In photovoltaic, silicon is by far the most popular material. Among the many renewable energy source applications, photovoltaic production is rising in prominence owing to its many unique benefits, such as its simplicity of allocation, high

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reliability, lack of fuel expense, cheap maintenance, and absence of noise and wear associated with moving components [2]. During periods of average or low peak needs, the utility utilizes a bidirectional meter to send extra energy to the grid, using the idea of net metering. Only in situations when maximal power extraction using Maximum Power Point Tracking (MPPT) is possible may grid-connected solar inverters provide active electricity [3, 4]. Since most electrical loads are inductive, their inductive reactive power consumption is higher. At this time, reactive electricity can only be generated by the grid. As more and more Distributed Generation (DG) units enter the grid and provide only active power, the site power factor degrades from an efficiency perspective, impacting grid performance. In the past, FACTS devices were used to inject or absorb reactive power in order to address power quality concerns. The huge size, expensive price, and extensive installation space that these devices need are some of its drawbacks. Because it could affect voltage regulation, controlling the network's reactive power flow is essential. Grid voltage regulation will be improved and the demand for expensive capacitor banks will be reduced as the number of grid-connected inverters increases and their usage as VAR compensators becomes more common. This study explores control algorithms for grid-connected solar inverters that may provide reactive power alongside active electricity, regardless of the load or irradiance. In the unique instance of inductive or capacitive load connections, there will be a significant shift in bus voltage, more than what is specified for the system, leading to unstable operation. A distributed control method is suggested for controlling the reactive power output in order to maintain grid-connected voltage stability. As a backup technique, active power reduction is used to regulate the voltages in the PV system [5–7]. Many studies highlight the issues with connecting large-scale PV systems to the grid, active power regulation, reactive power management, and low voltage crossing approaches [8–11].

Renewable energy is a dynamic field that is always changing to meet the demands of a world where fossil fuels are becoming scarcer and environmentally harmful. Thanks to its accessibility, minimal noise, and cheap cost, photovoltaic energy production is gaining popularity in both rural and urban regions. Distributing electricity in rural areas is a frequent usage of microgrids [1]. Microgrids may be either grid connected or operated independently. In freestanding photovoltaic microgrids, the solar power plant is not linked to the grid. Some machinery, like three-phase motors, cannot handle voltage imbalances that occur when the load is not evenly distributed, and this plant is not equipped to handle them [8]. In addition, when the weather is not nice, a PV system that is not connected to an energy storage system will not be able to keep up with the demand during the day and at night [9]. Harmonics are introduced into a system when power converters are utilized.

One of the main challenges facing the electrical industry is improving power quality, which is exacerbated by factors such as the growing reliance on sensitive electronic circuits in both homes and businesses, the rise of privatization in the energy sector, and competition among electric energy providers. Unwanted current flowing through the source is what causes harmonics, which in turn distort the voltage and create loss. Additionally, it has the potential to cause control components such as relays and mains to malfunction. This means that harmonic reduction is an absolute must. Numerous methods exist for mitigating the impact of harmonics [5, 10].

Using SAPF is one of these approaches; it cancels out the system's harmonic current by producing a harmonic current of the same amplitude and polarity. Its quick reaction speed and adaptability are attributes of the power electrical gadgets it incorporates. The Shunt Active Power Filter (SAPF) may inject power produced by unorthodox sources, compensate for harmonics and current distortion, and more [3]. The SAPF is an example of a VSI, or load-related voltage source inverter. The Shunt Active Power Filter maintains a balanced and sinusoidal after-remuneration current for a variety of load circumstances. When converting DC power to AC power, power switching devices come in handy. This causes the output waveforms to consist of discrete values, making the output less filtered and more oscillatory. The dictatorial regulatory approach dictates the time and duration that power values may become active, as well as their ability to provide near sine waveforms around the key repetition.

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The use of Static Volt-Ampere Reactive Compensators (SVCs) is also important for transient stability improvement, grid capacity expansion, and voltage regulation [4, 2]. The effective conversion of electromagnetic waves into energy is a hurdle that must be overcome in order for PV cells to be integrated. In order to get the most out of the electricity that the PV array produces, the Maximum Power Point Tracking (MPPT) method that is used in the system is essential. One of the biggest problems with MPPT methods is automatically detecting the voltage or current MPP [6]. The effect of variations in output voltage on the properties of MPPT outputs adds another layer of difficulty to this problem [7].

The extra features needed by current inverter levels cause them to be somewhat inaccurate, even if MPPT approaches have their benefits. The time needed to anticipate the Global Maximum Power Point (GMPP) is proportionate to the number of PV arrays and the complexity of the system design, making this mistake all the more crucial [11]. Power quality concerns may be resolved by deploying Distributed Flexible AC Transmission System (DFACTS) devices at the point of common coupling (PCC) that include control algorithms. Examples of programs that modify voltage, impedances, and power to enhance system dynamics include DSTATCOM and UPQC.

Series, shunt, series-series, and shunt-series are the four main categories into which devices fall [12, 13]. The shortcomings of conventional control algorithms rooted in IRPT and synchronous reference frame theory include sluggish response and unstable operation.

REVIEW ON PI-BASED REACTIVE POWER CONTROL SYSTEM IN GRID INTEGRATION

Here, we take a look at how different PI-based reactive power control systems have been used to improve power quality in grid integration of small-scale photovoltaic systems, as shown in Table 1. These systems include distributed power flow controllers, fuzzy adaptive PI controllers, optimal fractional order PID controllers, fuzzy PID controllers, and multi-stage fuzzy-based flexible controllers [14–17]. The computing load and the difficulty of testing in real-time systems are two examples of the limits.

Grid synchronization techniques, automated filtering mechanisms, and PI-based reactive power control systems are just a few of the downsides. Phase Locked Loop, DQ current control theory, Vector-based synchronization, Adaptive feed-forward PLL, lightweight inertial PLL, and mixed third and fourth-order complex filters were some of the grid synchronization approaches researched for their potential to enhance performance. There are a few problems with these methods, however. For example, PLLs only react temporarily to abrupt grid changes, instability occurs due to a lack of resilience, and precise and quick synchronization is required [18]. Arrays of AI techniques that rely on optimization have proven to be effective and dependable in the modern power network. However, there were a few drawbacks to these tactics, such as the difficulty of achieving accurate detection during dynamic operation, the need for effective decision-making in real-world circumstances, and so on [19, 20].

PHOTOVOLTAIC SYSTEM

To generate the required voltage and current, a photovoltaic system employs several strings of solar cells linked in parallel and series. The nonlinear I-V characteristic may be calculated using the PV equivalent circuit, as shown in Figure 1. Additionally, Figure 2 represents the mathematical model of PV array where NS and NP are the series and parallel cell numbers, respectively. When cells are connected in series, the output voltage is increased, and when they are connected in parallel, the output current is increased. Consequently, an array of cells with the required voltage and power levels is formed by connecting them in series and parallel. In the model that represents a single diode, the current flowing through the parallel diode may be expressed as:

$I_D = I_0 [\exp (q(V+IRs)/\alpha kt)-1]$ (1)

By using Kirchhoff's law in equivalent circuit of PV output current can be written as:

$I_{PV} = I_{PH} - I_D - I_r$… (2)

Table 1. This table provides a clear and concise overview of the studies, their focus areas, and key findings, making it easier to understand the scope and impact of each research effort.

Author(s)	Year	Focus	Key findings
Han *et al*. [1]	2020	Reactive power regulation ability of PV inverters	PV inverters exhibit good reactive power regulation; dynamic reactive power response time is within 30ms, exceeding national standards. Simulation and on-site tests confirm effectiveness.
Ibram *et al*. [10]	2020	Reactive power regulation in single-phase PV inverters	Discussed control strategies for reactive power compensation in single-phase PV inverters, emphasizing the role of renewables in replacing traditional coal power.
Tiwari *et al*. [8]	2021	Power plant controller for active/reactive power control in PV plants in India	Developed a power plant controller to meet grid code requirements. Real-time and HIL tests show the controller's effectiveness in managing active/reactive power output.
Karbouj *et al*. [2]	2021	Reactive power capability estimation and voltage control in PV inverters	Presented a self-adaptive voltage controller for PV inverters, accounting for environmental conditions. The strategy improves voltage control effectiveness and ensures grid code compliance under various conditions.
Liang Wang *et al*. [9]	2022	Reactive power and voltage stability in renewable energy integration	Proposed a coordinated control strategy for reactive power and voltage stability, validated via simulations. The strategy helps maintain stability amidst renewable energy's variability.
Yang *et al*. [12]	2019	Fast reactive power control in PV inverters	Studied the structure and reactive power control strategy of PV inverters. Simulation results in MATLAB/Simulink confirm the efficiency of the control strategy in a single-stage grid-connected PV system.
Wu *et al*. [4]	2022	Adaptive voltage control for PV grid-connected points	Proposed an adaptive voltage control strategy to mitigate voltage over-limit issues. Simulation results show improved voltage control by enhancing reactive power regulation of PV inverters.
Yan *et al*. [5]	2023	Multi-energy complementarity for clean energy systems	Introduced a reactive power coordination optimization strategy for a multi-energy system, enhancing energy supply-demand balance and promoting renewable energy consumption.
Zou *et al*. [18]	2023	Voltage fluctuation suppression in high-proportion PV HVDC systems	Proposed a reactive power coordination strategy to suppress voltage fluctuations caused by commutation failures. Simulation results demonstrate effectiveness in maintaining voltage stability.

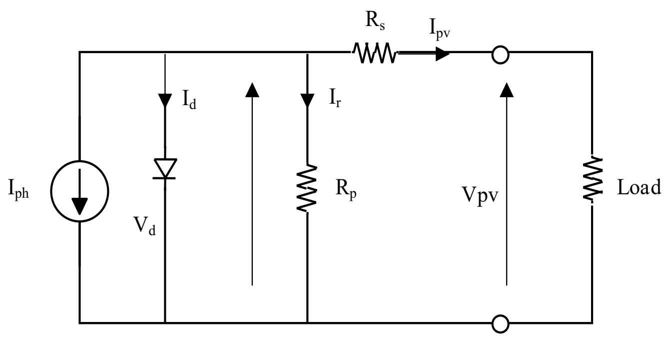

Figure 1. Equivalent structure of PV cell.

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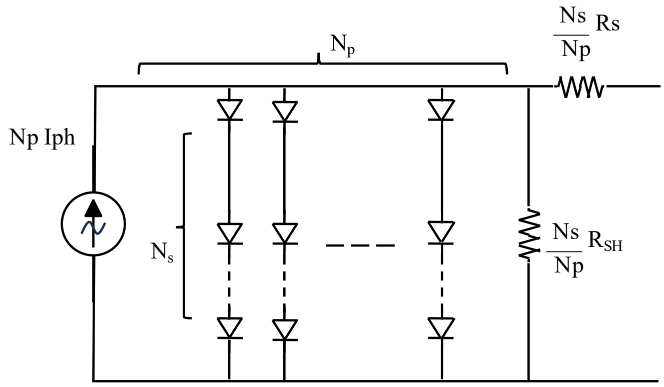

Figure 2. Mathematical model of PV array where NS and NP are the series and parallel cell numbers, respectively. When cells are connected in series, the output voltage is increased, and when they are connected in parallel, the output current is increased.

METHODOLOGY

Photovoltaic (PV) power plants that function on an exceedingly weak grid may achieve their objectives with the aid of adaptive reactive power regulation if you follow these steps in the technique. The goal of this approach is to enhance the power transfer capacity and voltage stability of PV systems via the implementation and verification of an adaptive control system. When trying to understand why renewable energy sources are underutilized, it helps to consider the actual grid conditions and the subsequent challenges. Public electricity networks in most European countries are designed with a spreading central configuration. Large conventional power stations may send their energy to grids. A transformer is a device that allows power to be aggregated by connecting the distribution and transmission grids. The consumer is not prioritized. By distributing electricity to its associated consumers, the interconnection acts as a central authority, either directly or indirectly. The distribution grid causes a voltage drop when electricity passes across it. How quickly it decreases is dependent on the inductance and resistance of the cable. As the cable lengthens, both of these factors grow. To make sure everyone has enough power, a transformer boosts the voltage at the cables beginning a little. Renewable energy plants must be located in areas with abundant energy supplies, such as areas with strong wind speeds, in order to produce enough power. Consequently, the installations are linked to the grid via a number of local locations. The capacity and integration of renewable power facilities at lower grid tiers is lower than that of big power plants. After connecting to low-voltage connections, dispersed generators may cause a change in conditions, with electricity flowing towards the transformer [16]. The integration of more and more dispersed generators worsens the issue of voltage rises in rural locations with often insufficient power infrastructure. The main problem is that the system cannot handle enough renewable energy. Integrating dispersed energy producers has a major influence on the overall grid's functioning since it increases the demands on the mains. Materials, efficiency, and producing costs are all negatively affected by these measures, which also increase carbon dioxide emissions and the usage of fossil fuels. In order to keep voltage spikes at bay, we must partly extend the grid. In other cases, the expense of fortifying a grid is not insignificant. The benefits of renewable energy sources are often believed to be less than the costs of producing them [4]. Moreover, Figure 3 represents the overall Simulink of adaptive reactive power control of photovoltaic power plants.

Another issue that alternative power producers have raised is that they are unable to verify the operator's claims on the technical and financial aspects of their grid connection due to a lack of information regarding the available grid capacity. Distribution System Operators (DSOs) is another name for electricity distributors. When a power company is involved in developing alternative energy initiatives, it is questionable if the DSO is entirely unbiased towards independent renewable energy producers. Due to a lack of transparency, the permission procedure for connecting to the grid is lengthy [2, 6]. In spite of grid challenges, stakeholders see renewable energy sources in a good light, according to the results.

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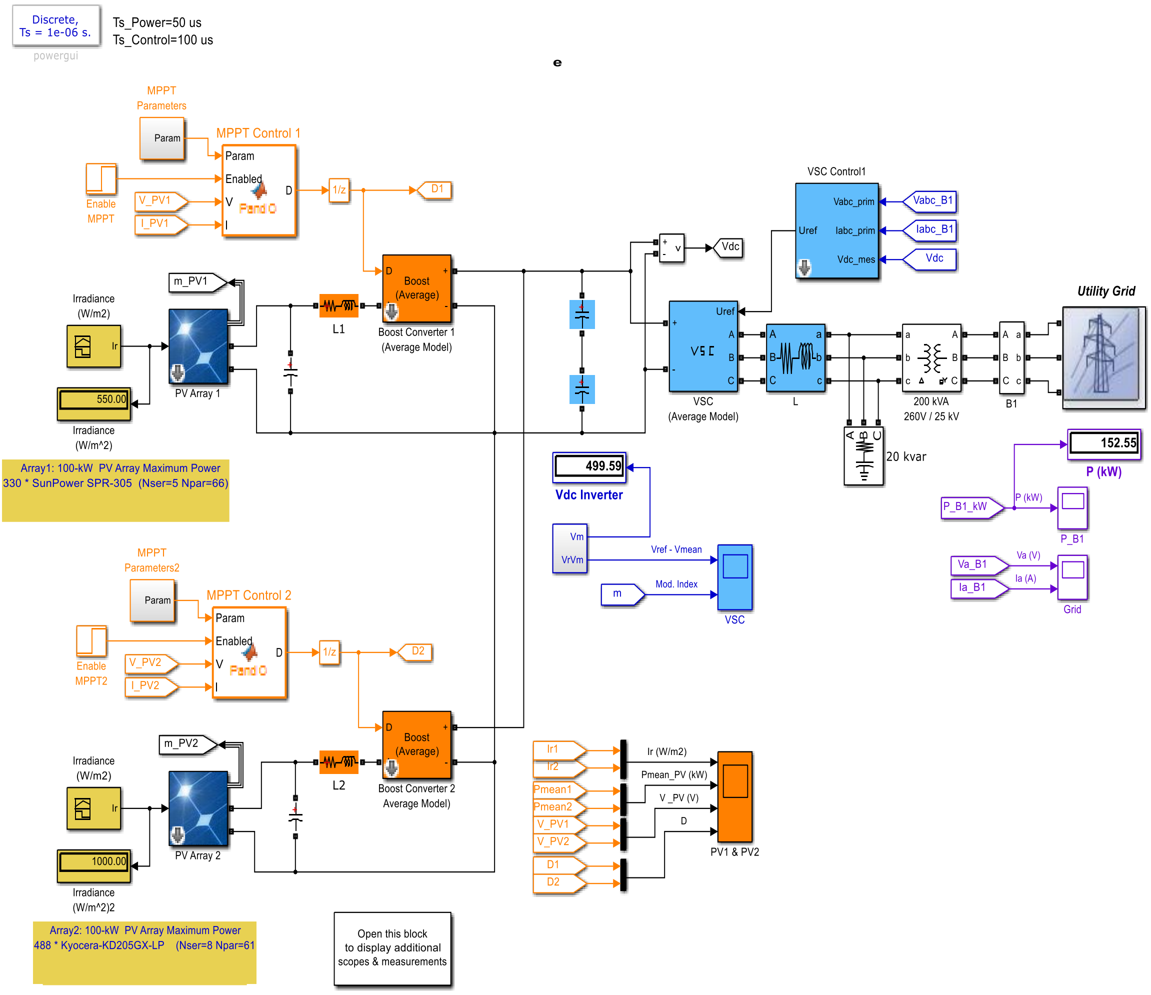

Figure 3. Overall simulink of adaptive reactive power control of photovoltaic power plants.

a. *System Modeling:* The PV power plant and grid are modeled mathematically. This model takes into account the inverter's dynamics, the PV array's characteristics, and the electrical behavior of the ultra-weak grid, which is characterized by high impedance and low short-circuit ratios (SCRs). Accurate dynamic representation is achieved by means of the model, which combines real-time observed grid properties including impedance, frequency, and voltage as shown in Figure 4. We test the proposed adaptive control method in a number of simulations with different ultra-weak grid configurations.
b. *Scenario Definition:* A number of possible grid states are detailed, including fluctuating short-circuit ratios (SCRs), altered grid impedance, and voltage disturbances. These cases mimic the difficulties, such as voltage instability, synchronization problems, and power transmission limits that PV plants might encounter in very weak networks as shown in Figure 5. In this simulation, we check how well the control system can track reactive power demand, impedance, and voltage in real time. The simulation tests the system's responsiveness to changes in the grid voltage by manipulating the reactive power output. Furthermore, Figure 6 represents the overall output of the system with respect to time.

The system's performance is evaluated using metrics such as:

- *Voltage Stability:* Measured by monitoring how effectively the adaptive control system mitigates voltage fluctuations and prevents instability.
- *Power Transfer Efficiency:* Analyzed in terms of the ability of the PV plant to transfer maximum possible power to the grid without causing voltage instability or system failures.

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- *Reactive Power Support:* The system's ability to provide adequate reactive power to stabilize grid voltage, especially during disturbances.

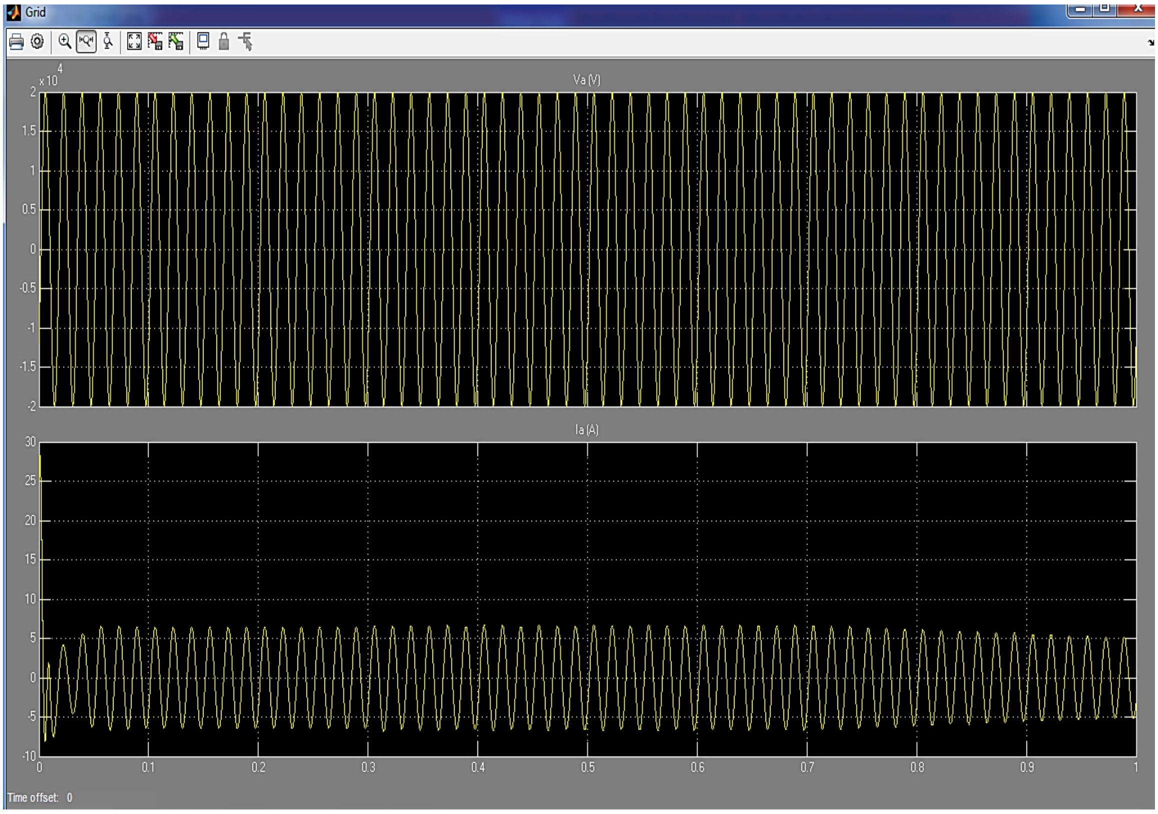

Figure 4. Voltage and current variations with respect to time.

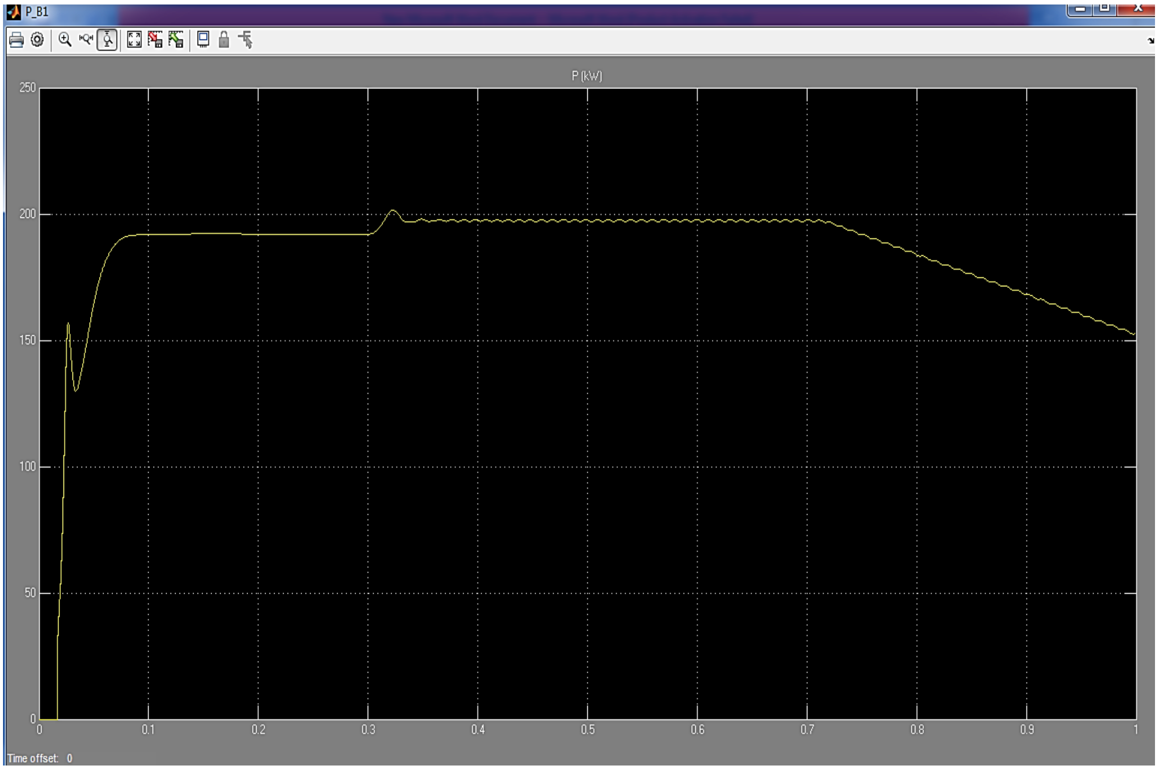

Figure 5. Power variations with respect to time.

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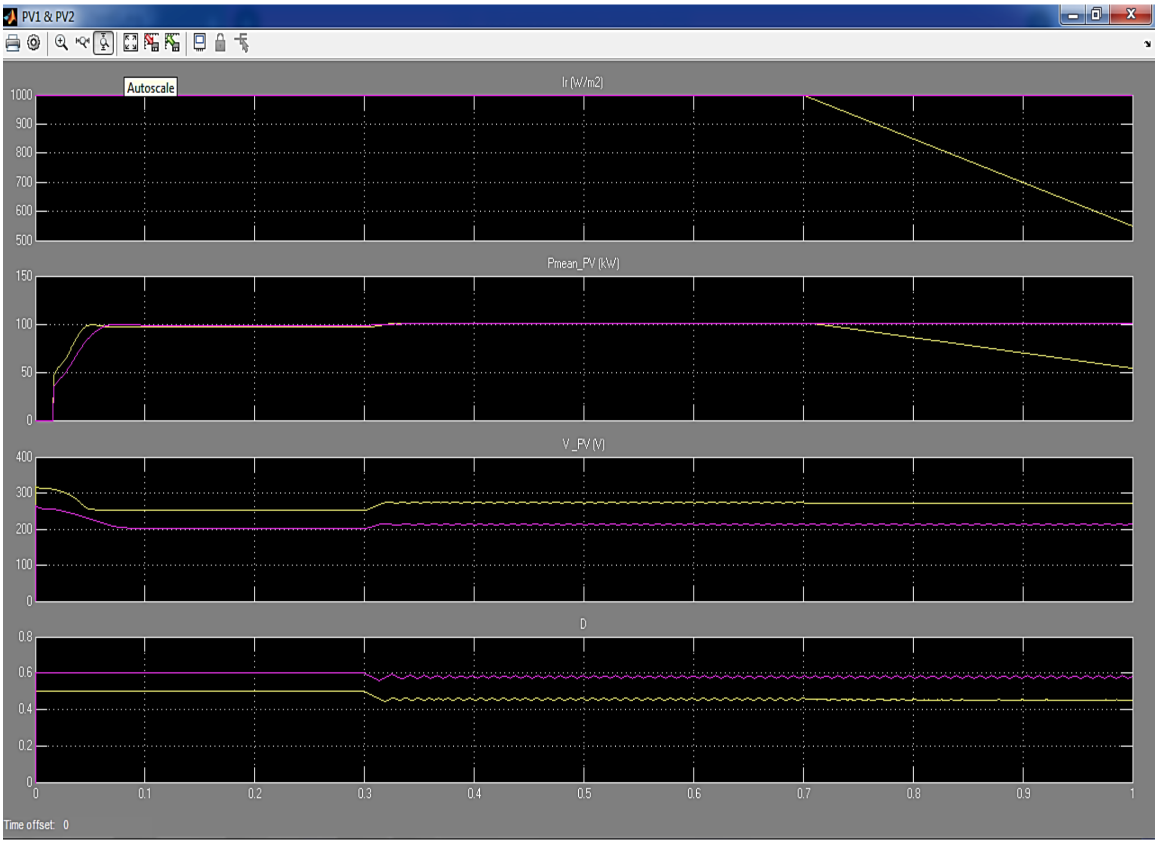

Figure 6. Overall output of the system with respect to time.

CONCLUSION

Because of their low short-circuit rates (SCRs) and unpredictable voltages, photovoltaic (PV) power plants are difficult to include into insufficient networks. In response to these problems, this research presented an ARPC method for adaptive reactive power regulation; this method allows PV plants to modify their reactive power output in response to grid circumstances in real-time. Utilizing intricate methodologies including adaptive gain tuning, voltage sensitivity analysis, and grid impedance estimations, the suggested solution is put forward. Renewable energy sources may be more widely used when reactive power compensation is optimized, allowing PV facilities to run dependably under adverse grid situations. In the future, scientists could try to refine this method.

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